LCA Case Studies

Life Cycle Assessment of Kerosene Used in Aviation

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Abstract

Goal, Scope, and Background. The main goal of the study is a comprehensive life cycle assessment of kerosene produced in a refinery located in Thessaloniki (Greece) and used in a commercial jet aircraft.

Methods. The Eco-Indicator 95 weighting method is used for the purpose of this study. The Eco-Indicator is a method of aggregation (or, as described in ISO draft 14042, 'weighting through categories') that leads to a single score. In the Eco-indicator method, the weighing factor (We) applied to an environmental impact index (greenhouse effect, ozone depletion, etc.) stems from the 'main' damage caused by this environmental impact.

Results and Discussion. The dominant source of greenhouse gas emissions is from kerosene combustion in aircraft turbines during air transportation, which contributes 99.5% of the total CO_2 emissions. The extraction and refinery process of crude oil contribute by around 0.22% to the GWP. This is a logical outcome considering that these processes are very energy intensive. Transportation of crude oil and kerosene have little or no contribution to this impact category. The main source of CFC-11 equivalent emissions is refining of crude oil. These emissions derive from emissions that result from electricity production that is used during the operation of the refinery. NO_x emissions contribute the most to the acidification followed by SO_2 emissions. The main source is the use process in a commercial jet aircraft, which contributes approximately 96.04% to the total equivalent emissions. The refinery process of crude oil contributes by 2.11% mainly by producing SO_2 emissions. This is due to the relative high content of sulphur in the input flows of these processes (crude oil) that results to the production of large amount of SO_2. Transportation of crude oil by sea (0.76%) produces large amount of SO_2 and NO_x due to combustion of low quality liquid fuels (heavy fuel oil). High air emissions of NO_x during kerosene combustion result in the high contribution of this subsystem to the eutrophication effect. Also, water emissions with high nitrous content during the refining and extraction of crude oil process have a big impact to the water eutrophication impact category.

Conclusion. The major environmental impact from the life cycle of kerosene is the acidification effect, followed by the greenhouse effect. The summer smog and eutrophication effect have much less severe effect. The main contributor is the combustion of kerosene to a commercial jet aircraft. Excluding the use phase, the refining process appears to be the most polluting process during kerosene's life cycle. This is due to the fact that the refining process is a very complicated energy intensive process that produces large amounts and variety of pollutant substances. Extraction and transportation of crude oil and kerosene equally contribute to the environmental impacts of the kerosene cycle, but at much lower level than the refining process.

Recommendation and Perspective. The study indicates a need for a more detailed analysis of the refining process which has a very high contribution to the total equivalent emissions of the acidification effect and to the total impact score of the system (excluding the combustion of kerosene). This is due to the relative high content of sulphur in the input flows of these processes (crude oil) that results to the production of large amount of SO_2.

Keywords: Aviation; environment; kerosene; life cycle impact assessment (LCIA)

Introduction

Civil aviation has enjoyed fast growth for a long time. The air transport industry, as well as related industries such as the aeronautical industry and tourism, is growing at rates clearly above the average growth of the economy of the European Union. For the next few decades, 4% to 5% traffic increase per annum has been predicted. Saturation of world wide air traffic is still far away; even in areas with the most advanced air traffic systems, like the USA or Europe, there is still strong growth. However, technology improvements are not sufficient to balance traffic growth: fuel consumption and hence CO_2 emissions increase by some 2% per annum, in contradiction to the accepted requirements of protecting the atmosphere (Kyoto Protocol). Air transport is considered to be contributing through the emission of gases and particles from aircraft engines to changes in air quality at the Earth's surface, in climate, and in the stratospheric ozone loss, thus affecting the UV-B radiation at the surface. The question of how significant emissions and their effects are of particular importance for future policy priorities [1,2,3].

Life cycle assessment (LCA) has been used to study the environmental impacts of kerosene used in aviation. LCA is a powerful tool, often used as an aid to decision making in industry and for public policy. LCA forms the foundation of the newly-invented field of industrial ecology. There are several possible uses for this tool. It can be used to evaluate the impacts from a process or from production and use of a product. Impacts from competing products or processes can be compared to help manufacturers or consumers choose among options, including foregoing the service the product or process would have provided because the impacts are too great. In this study, LCA is used to identify key process steps and, most important, key areas of an energy system where process changes could significantly reduce impacts. Analysts can use the results to help characterize the ramifications of possible policy options or technological changes.

Generally, an energy system is a complete system for generating, supplying and using energy in a given context such as a country or region that can be defined in terms of borders with known energy import and export figures. The physical components of an energy system would typically be a number of facilities for extracting, importing or collecting energy, then for treating (e.g. refining), and successively converting the energy along a chain of steps leading to the final conversion at the end-user. Along the way, transport takes place between points of intermediary conversion, according to the layout and operation of the overall energy network.

The impacts of the energy system may be negative, positive or neutral. Usually the provision of energy is the primary positive impact. Other impacts affect people working with the energy system or in some cases the general public. Similarly, there may be impacts on the close and on the more distant environment, effecting both the physical and the biological environment.

The LCA process is a systematic, phased approach and consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. The procedures for performing the inventory part of an LCA have been very well defined by such groups as the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO) [4,5].

1 Goal, Scope and Background

The main goal of the study is a comprehensive life cycle assessment of kerosene produced in a Greek refinery and used in a commercial jet aircraft. Kerosene (approximately 325 to 575°C boiling range) and wide-cut (approximately 125 to 575°C boiling range) types of fuels are generally straight-run stocks taken directly from selected crudes by fractional distillation. Kerosene is usually made by a single cut. Wide-cut fuels can be made the same way, or they may be a blend of a kerosene boiling fraction plus a lighter stock such as heavy straight-run gasoline or another material in this boiling range. Processing, including desulfurization, sweetening, or other treatment can be employed to remove minor undesirable constituents. Such treatment can be kept to a minimum by utilising low sulfur content crude oils. Civilian aircraft primarily use Jet A or Jet A-1 fuel as defined by ASTM D1655 [6].

The data used for the purposes of this study come from different sources. Literature data was used for the extraction process, transportation phases and the combustion of kerosene [7,8,9,10,11,12,13,14,15,16,17,18,19,20]. On the other hand, raw data from the refinery located in Thessaloniki-Greece was used for the emissions that derive from the production process of kerosene [21]. The overall quality of the data is considered to be good and adequate for the requirements of this study.

1.1 System boundaries

A general production chain of kerosene is illustrated in **Fig. 1**. Greek refineries are mainly importing crude oil that is extracted in oil wells located in the Middle East. **Table 1** illustrates the origin of the crude oil that is used in the refinery and the corresponding sulphur content [21].

Table 1: Crude oil input

Oil type	%	Sulphur content wt %
Arabian light	26.3	1.79
Arabian medium	56.8	2.43
Iranian heavy	2.9	1.70
Russian	4.9	1.25
Zeit Bay	5.1	1.36
Domestic	4.0	3.10
	100	2.154

Crude oil usually contains considerable quantities of emulsified water, occasionally as much as 80 to 90%. Pipelines do not accept crude oils having more than 2%, sometimes even specifying 0.5% or less. The excess is removed before the crude oil can be transported to the refinery. Three separate types of processes are used for modeling of the extraction process: onshore production, offshore production and enhanced recovery. The shares of the total crude oil extracted by each process are presented in **Table 2** [7].

Petroleum, as well as its products, is transported to and from a refinery by pipelines, tankers, railroads and motor trucks. From the Middle East the oil is transported to Greece by tankers. Tankers in some instances transport over 700,000 bbl of crude oil in one trip. A mean value of 10000 km has been used for a two way trip of a tanker between Middle East and a refinery located in Thessaloniki, Greece.

Table 2: Production of crude oil by technology type [7]

Technology type	Crude oil production
Conventional onshore	77%
Conventional offshore	20%
Enhanced / Advanced	3%

Fig. 1: Life cycle chain of kerosene

Table 3: Weight distribution of refinery products [21]

Refinery product	wt %
Propane	0.31
LPG	1.93
Gasoline	9.35
Jet fuel - Kerosene type	**7.69**
Diesel	24.32
Mazout No1	2.62
Mazout No3	21.90
Heavy Oil	14.11
Vacuum Gas Oil	4.42
Asphalt	3.76
Liquid sulphur	0.31
Intermediate products	
Gas products	1.59
Liquid products	1.59
Varsol	2.07
Naphtha	4.04
Total	100.00

Crude oil and refined products are stored in concrete reservoirs and steel tanks. Concrete reservoirs may hold several million barrels of crude oil. Steel tanks vary in size. They usually hold from 50,000 to 120,000 bbl. The distribution of product kerosene from the refinery is complicated. Kerosene may be shipped to large terminals and then reshipped to distributing centers, from which they are delivered to the customers [8,9,10,11].

Kerosene is only one of the products that are produced from the refining of crude oil. Different products must therefore be allocated their proportional share of the total energy consumption and emissions from production platforms, terminals and the refinery [12]. Allocation can be made depending on mass, volume, energy content, economical value or other relevant parameters for different product flows. The weight distribution of finished products from the refinery under study is presented in **Table 3**. For the purpose of this study, all the refinery emissions have been allocated according to the mass of kerosene. For every 100 kg of crude oil processed, 7.69 kg kerosene is produced [21]. The production of 1 kg of kerosene has been used as the functional unit of the LCA study.

Fig. 2 illustrates the chain of conversions of kerosene leading to the final energy consumer, which is civil aviation. A very large number of environmental burdens result from the operation of the kerosene cycle. These may be characterized as emissions to air, waste water, solid wastes and other burdens. The environmental impact of the production of kerosene depends on the composition of the product and of the performance of the production unit. High quality product normally requires higher energy consumption in the refinery process and therefore leads to higher emissions. The technological choices made are an important parameter for the energy system.

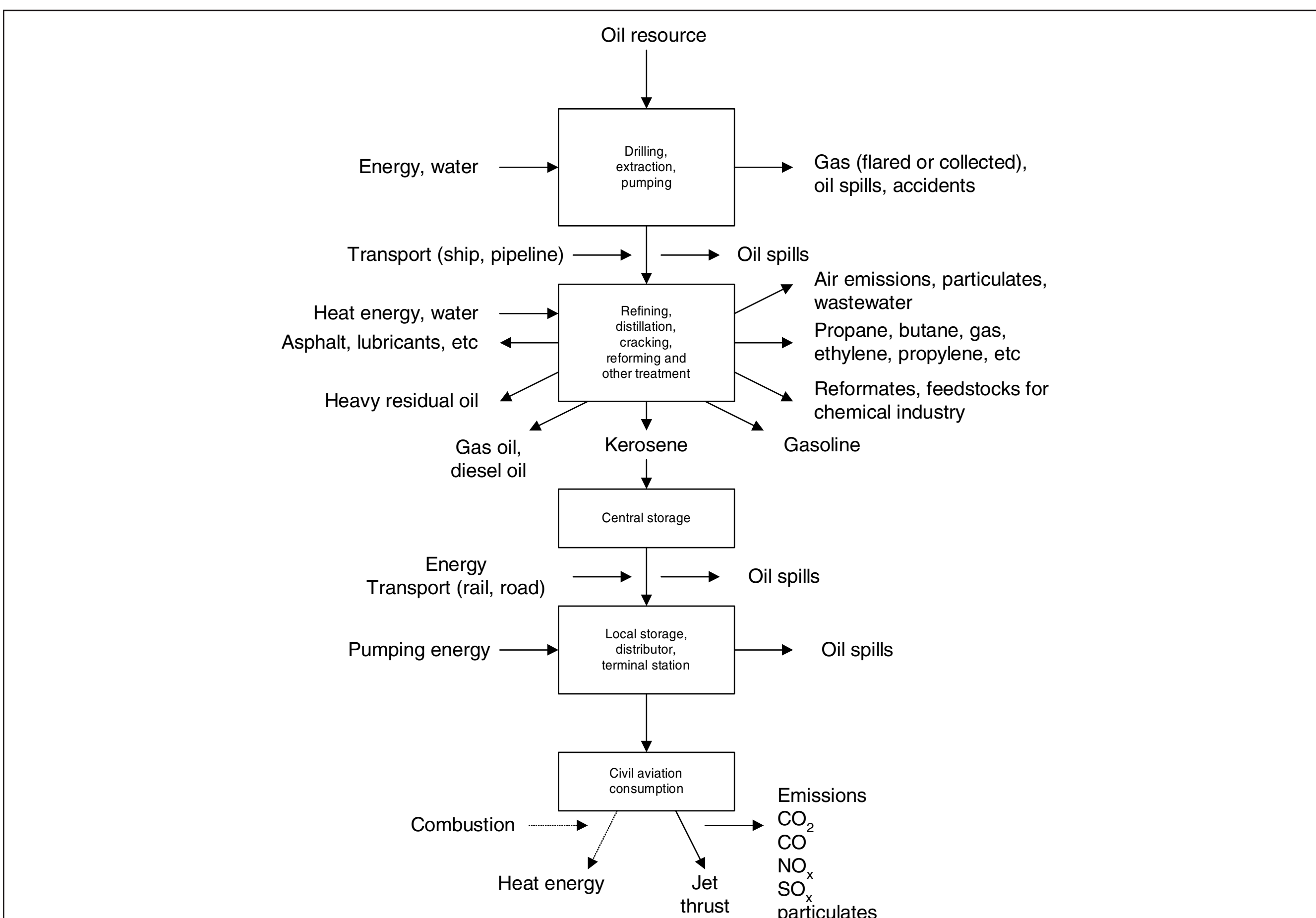

Fig. 2: Kerosene usage chain with indications of inputs and outputs including environmental impacts

2 Impact Assessment

During the impact assessment step it is tried to understand and evaluate the magnitude and significance of the potential environmental impacts of the life cycle of kerosene. Impact assessment consists of three steps: classification, characterisation and evaluation.

The Eco-Indicator 95 weighting method is used for the purpose of this study [22]. The Eco-Indicator is one method of aggregation (or, as described in ISO draft 14042, 'weighting through categories') that leads to a single score. In the Eco-indicator method, the weighing factor (We) applied to an environmental impact index (greenhouse effect, ozone depletion, etc.) stems from the 'main' damage caused by this environmental impact. This main damage may be one of the following:

- five percent ecosystem impairment,
- one extra death per million inhabitants per year,
- health complaints as a result of smog episodes.

These damages are considered equivalent, which is a purely subjective valuation.

2.1 CO_2 equivalent emissions and the 'greenhouse effect'

Greenhouse gases are those gases, which contribute, directly or indirectly, to global climate change. The relative contribution of different gases to climate change is complex. Each has a different infra-red absorptive capacity (forcing factor), but also a different lifetime, so that relative contributions over time vary. The most common indicator is the 100 year Global Warming Potential (GWP). This is defined as the contribution of unit mass of a gas to radiative forcing over 100 years relative to unit mass of carbon dioxide.

Carbon dioxide emissions have been responsible for most anthropogenic global warming over the last century, and they will remain the most important contributor. CO_2 emissions, of the kerosene life cycle, are also the major contributor to the total greenhouse gas effect.

Fig. 3 displays the equivalent emissions of CO_2 and the corresponding effect of each subsystem of the life cycle of kerosene to the greenhouse effect.

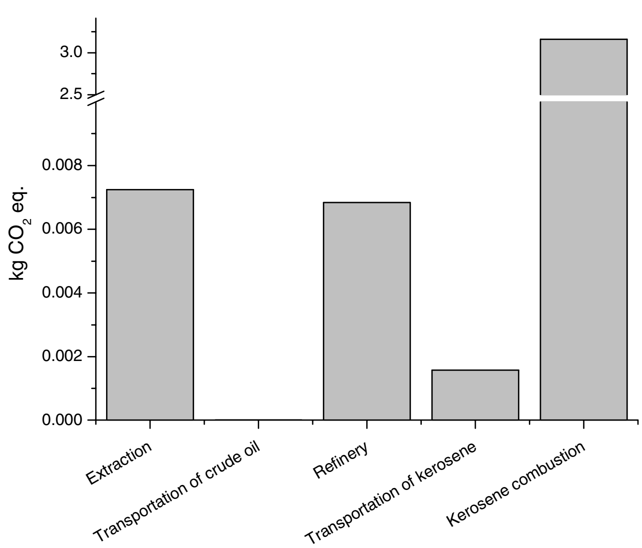

Fig. 3: CO_2 equivalent emissions of life cycle of kerosene per subsystem

2.2 CFC-11 equivalent emissions and the ozone depletion effect

The ozone layer is present in the stratosphere and acts as a filter absorbing harmful short wave ultraviolet light whilst allowing longer wavelengths to pass through. A decline in the ozone layer allows more harmful short wave radiation to reach the Earth's surface, potentially causing changes to ecosystems as different flora and fauna have varying abilities to cope with it.

2.3 SO_x (or SO_2) equivalent emissions and the acidification effect

Acidification is measured as the amount of protons released into atmosphere. The weighting factors are presented either as mol H+ or as kg of SO_x equivalent. The two types of compound mainly involved in acidification are Sulphur and Nitrogen compounds. Chemicals like ammonia, HF, HCl and NO_x contribute to this impact category. SO_2 and SO_x emissions are considered to have the same effect in this impact category (**Fig. 4**).

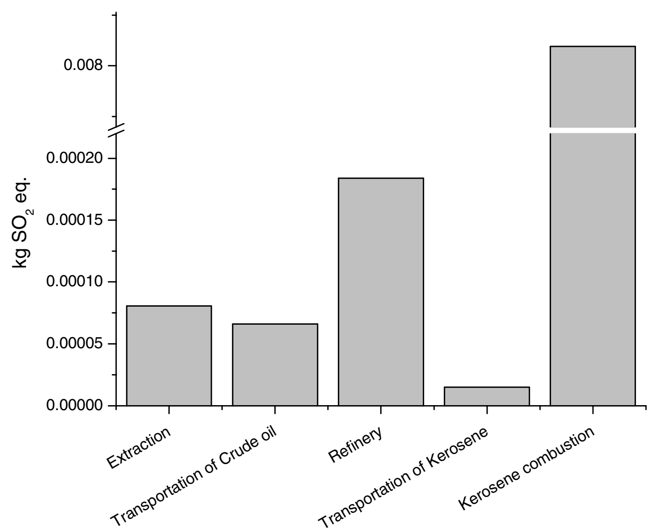

Fig. 4: SO_2 equivalent emissions of life cycle of kerosene per subsystem

2.4 Phosphate equivalent emissions and the eutrophication effect

Nitrogen and phosphorus are essential nutrients for the regulation of ecosystems. Enrichment (or eutrophication) of water and soil with these nutrients may cause an undesirable shift in the composition of species within the ecosystems. Eutrophication of terrestrial ecosystems is mainly due to (long distance transport of) atmospheric emissions of NO_x (nature areas) and emissions to soil of nitrogen and phosphorus (agricultural areas).

Nutriphication potentials are available for all important eutrophying compounds. It is important to note that there are available nutriphication potentials for compounds to air and to water. For this reason we study separately the emissions which are released to air from them which are realeased to

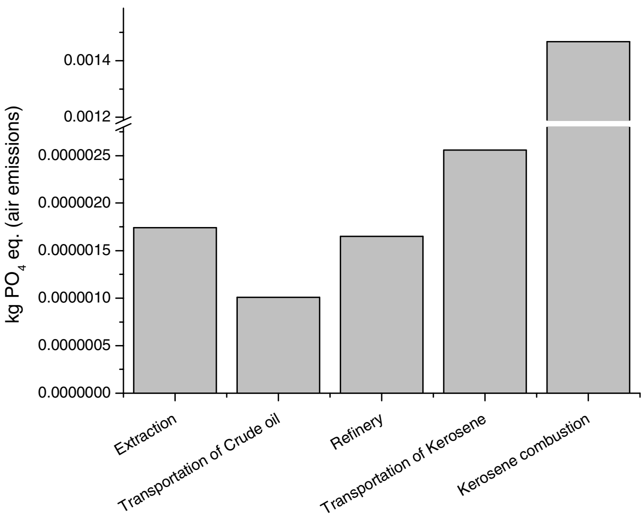

Fig. 5: Eutrophication equivalent air emissions per subsystem

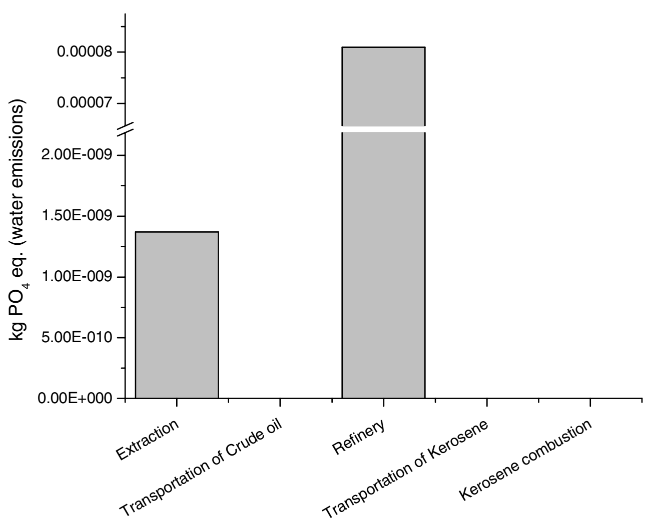

Fig. 6: Eutrophication equivalent water emissions per subsystem

water. **Fig. 5** and **6** display the equivalent emissions of PO_4 and the corresponding effect of each subsystem of the life cycle of kerosene to the eutrophication effect.

2.5 B(a)P equivalent emissions and Carcinogenesis

Chemical compounds like Benzo(a)pyrene, Chrome, Benzene, Nikel, Polycyclic Aromatic Hydrocarbons (PAH) and other are considered to be responsible for Carcinogenesis. Thus, all the emissions are calculated on a equivalent basis which are relevant to this impact (**Fig. 7**). The main source of this kind of emissions during the life cycle of kerosene is the refinining process of crude oil.

2.6 Winter smog effect

For evaluating winter smog, the Winter Smog Potentials (WSP) are used for converting the different chemical emissions (dust, SO_2) to an equivalent basis. In this case, SO_2 is used as the equivalent chemical compound (**Fig. 8**).

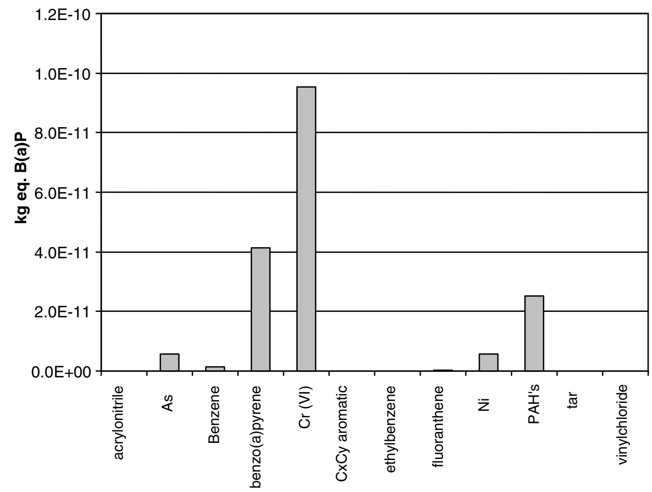

Fig. 7: B(a)P equivalent emissions of the life cycle of kerosene

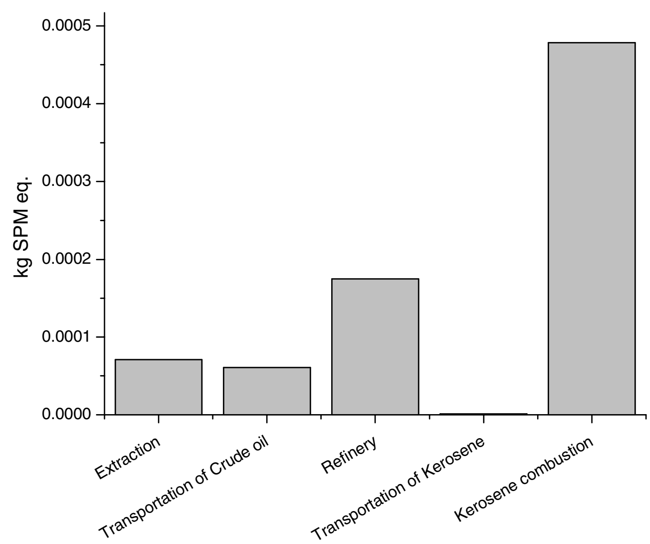

Fig. 8: Winter smog equivalent emissions

2.7 Heavy metals

This category refers to the releases of heavy metals to the environment. For evaluating the total contribution, the emissions of all the chemical compounds of this category (e.g. Cd, Hg, Mn, Pb, As, Cr, Sb, Cu) are converted into equivalent emissions of lead (Pb) in water (**Table 4**).

Table 4: Equivalent emissions (water) of Pb of the kerosene life cycle

Heavy metal	kg eq. Pb
As	9.72E-12
B	2.21E-12
Ba	1.57E-10
Cd	8.59E-12
Cr	7.57E-12
Cu	6.19E-14
Hg	2.1E-13
Mn	2.45E-11
Mo	4.66E-12
Ni	1.76E-11
Pb	3.01E-10
Sb	0

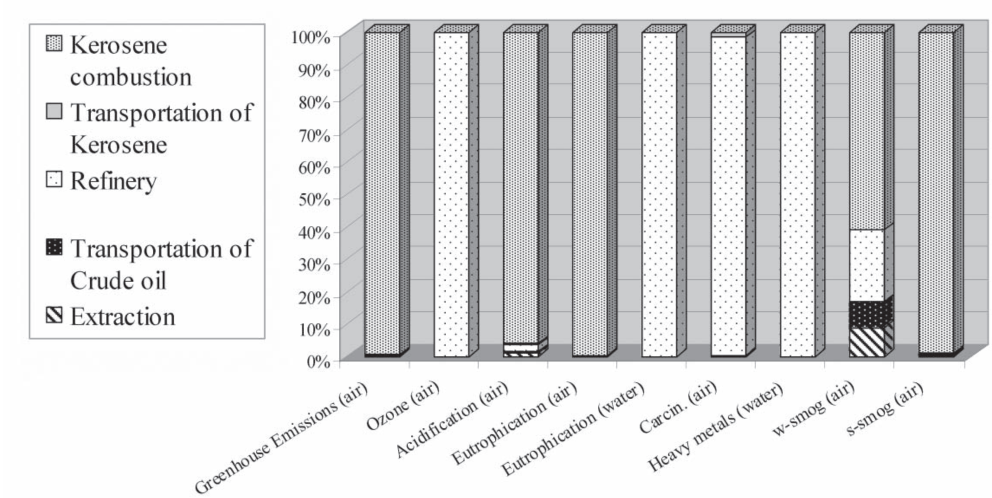

Fig. 9: Environmental effects calculated on the basis of the impact tables of the life cycle of kerosene

Finally, a histogram is displayed (**Fig. 9**) showing a number of environmental effects calculated on the basis of the impact table. All effects are scaled to 100 percent, and each column represents the impacts arising from different processes and materials in the assembly.

With all effects scaled to 100 percent, it is not very easy to see which parts of the assembly have the highest overall environmental impact. Each bar on the histogram could represent 100 percent of a very large impact, or equally, 100 percent of a small one. The next step of the study will be normalisation and evaluation of the impacts.

3 Normalization and evaluation

Normalization is defined as an optional element relating all impact scores of a functional unit to the impact scores of a reference situation. This reference situation may be so-called actual flows of a certain region, but also variations in space or time of these. The main aim of normalization is therefore to relate the environmental burden of a product to the burden in its surroundings.

In this study, normalization values for the European territory are used. The calculation of normalization values (**Table 5**) have been carried out using the data on resource extraction and emissions, which have been collected previously in a normalization study carried out for the Dutch ministry of transport and public works and the Dutch ministry of Housing, Spatial planning and the Environment.

Normalization only reveals which effects are large, and which effects are small, in relative terms. It says nothing of the relative importance of these effects. Evaluation factors are used for this purpose. Here, a weighting factor has been applied, scaling the results to a certain level of seriousness. This seriousness is measured in indicator points. **Table 6** presents the normalization and evaluation weighting factors used for the purpose of this study.

Table 6: Normalization and evaluation factors [22]

Impact category	Normalization	Evaluation
Greenhouse	0.0000742	2.5
Ozone depletion	1.24	100
Acidification	0.00888	10
Eutrophication	0.0262	5
Heavy metals	17.8	5
Carcinogenesis	106	10
Winter smog	0.0106	5
Summer smog	0.0507	2.5
Solid waste	0	0

Table 5: Normalization of the impact table of the kerosene life cycle

	Extraction	Transportation of Crude oil	Refinery	Transportation of Kerosene	Kerosene combustion	Total
Greenhouse emissions (air)	5.37E-07	2.49E-10	5.08E-07	1.16E-07	2.34E-04	**2.36E-04**
Ozone depletion(air)	0	0	1.84E-10	0	0	**1.84E-10**
Acidification (air)	7.17E-07	5.87E-07	1.63E-06	1.33E-07	7.44E-05	**7.75E-05**
Eutrophication (air)	4.56E-08	2.64E-08	4.32E-08	6.70E-08	3.85E-05	**3.86E-05**
Eutrophication (water)	3.59E-11	0	2.12E-06	0	0	**2.12E-06**
Carcinogenesis (air)	7.90E-11	0	1.82E-08	2.57E-10	0	**1.86E-08**
Heavy metals (water)	0	0	9.49E-09	0	0	**9.49E-09**
w-smog (air)	7.51E-07	6.43E-07	1.85E-06	1.32E-08	5.07E-06	**8.33E-06**
s-smog (air)	3.02E-07	2.54E-07	4.33E-07	3.77E-07	1.09E-04	**1.10E-04**

Table 7: Indicator graph showing the total impacts of the kerosene life cycle

	Extraction	Transportation of Crude oil	Refinery	Transportation of Kerosene	Kerosene combustion	Total
Greenhouse emissions (air)	1.34E-06	6.23E-10	1.27E-06	2.91E-07	5.86E-04	**5.89E-04**
Ozone depletion (air)	0	0	1.84E-08	0	0	**1.84E-08**
Acidification (air)	7.17E-06	5.87E-06	1.63E-05	1.33E-06	7.44E-04	**7.75E-04**
Eutrophication (air)	2.28E-07	1.32E-07	2.16E-07	3.35E-07	1.92E-04	**1.93E-04**
Eutrophication (water)	1.80E-10	0	1.06E-05	0	0	**1.06E-05**
Carcinogenesis (air)	7.90E-10	0	1.82E-07	2.57E-09	0	**1.86E-07**
Heavy metals (water)	0	0	4.74E-08	0	0	**4.74E-08**
w-smog (air)	3.76E-06	3.22E-06	9.27E-06	6.61E-08	2.54E-05	**4.17E-05**
s-smog (air)	7.54E-07	6.34E-07	1.08E-06	9.42E-07	2.73E-04	**2.76E-04**
Total	**1.33E-05**	**9.85E-06**	**3.90E-05**	**2.97E-06**	**1.82E-03**	

Finally, the evaluation scores are added up to give a total impact for each material and process in the assembly. The 'indicator' table is showing the total impacts of the kerosene life cycle (**Table 7**).

4 Results and discussion

The main results that can be extracted from the inventory created for the life cycle assessment of kerosene are:

Global warming potential. CO_2 emissions are the major contributor to the greenhouse gas effect. The dominant source of greenhouse gas emissions is from kerosene combustion in aircraft turbines during air transportation, which contributes 99.5% of the total CO_2 emissions (**Fig. 10**). The extraction and refinery process of crude oil contribute by around 0.22% to the GWP. This is a logical outcome considering that these processes are very energy intensive. Transportation of crude oil and kerosene have little or no contribution to this impact category.

Ozone depletion effect. The main source of CFC-11 equivalent emissions is refining of crude oil. These emissions derive from emissions that result from electricity production that is used during the operation of the refinery.

Acidification effect. NO_x emissions contribute the most to the acidification followed by SO_2 emissions. The main source is the use process in a commercial jet aircraft, which contributes approximately 96.04% to the total equivalent emissions (**Fig. 11**). The refinery process of crude oil contributes

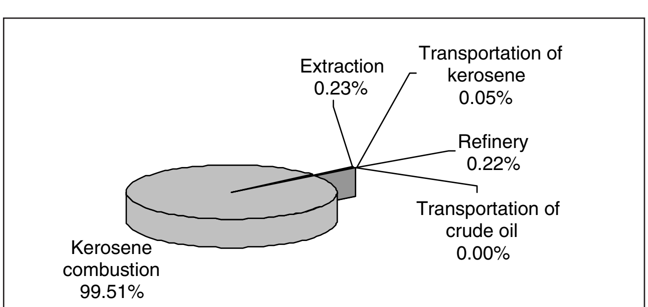

Fig. 10: Percentage contribution to the GHG emissions

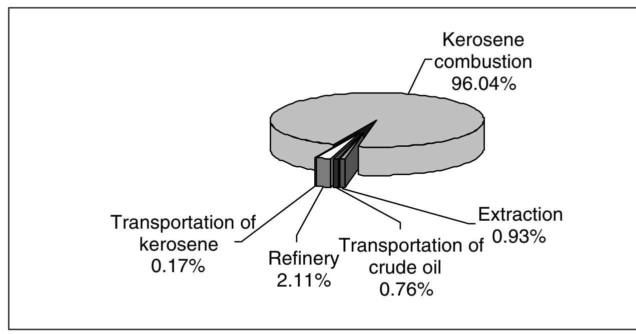

Fig. 11: Percentage contribution to the acidification effect

by 2.11% mainly by producing SO_2 emissions. This is due to the relative high content of sulphur in the input flows of these processes (crude oil) that results to the production of large amount of SO_2. Transportation of crude oil by sea (0.76%) produces large amount of SO_2 and NO_x due to combustion of low quality liquid fuels (heavy fuel oil).

Eutrophication effect. High air emissions of NO_x during kerosene combustion result in the high contribution of this subsystem to the eutrophication effect. Also, water emissions with high nitrous content during the refining and extraction of crude oil process have a big impact to the water eutrophication impact category.

5 Conclusions

The main results that derive from the normalization and evaluation procedure are:

- The major environmental impact from the life cycle of kerosene is the acidification effect, followed by the greenhouse effect. The summer smog and eutrophication effect have much less severe effect.
- The main contributor is the combustion of kerosene to a commercial jet aircraft.
- Excluding the use phase, the refining process appears to be the most polluting process during kerosene's life cycle. This is due to the fact that the refining process is a very complicated energy intensive process that produces large amounts and variety of pollutant substances.

- Extraction and transportation of crude oil and kerosene equally contribute to the environmental impacts of the kerosene cycle, but at much lower level than the refining process.

The study indicates a need for a more detailed analysis of the refining process which has a very high contribution to the total equivalent emissions of the acidification effect and to the total impact score of the system (excluding the combustion of kerosene). This is due to the relative high content of sulphur in the input flows of these processes (crude oil) that results to the production of large amount of SO_2.

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Preamble

This series of two papers which is based on a Diploma Thesis (N. Stylos, 2000) presents the LCA performed for a Multicrystalline Photovoltaic (PV) system and a full scale application on an island. **Part 1** presents an energy analysis for all the PV components, extended to the primary energy carriers. In **Part 2**, a complete and accurate identification and quantification of air emissions, water effluents, and other life-cycle outputs is performed, for an installation of a multicrystalline photovoltaic park on a Greek island.